Nature of Vowel Sounds.

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II.

IN a preceding paper (NATURE, January 13, p. 632) it was explained that the analysis of vowel curves showed (1) that the fundamental, or voice tone, must consist of a series of puffs, and not of smooth vibrations; and (2) that the overtones, or the specific vowel tones, must be quite independent of the fundamental—that is, they can just as well be inharmonic as harmonic to it.

The Manufacture of Vowels.

For the manufacture of vowels Helmholtz used tuning-forks that gave smooth vibrations and not puffs; moreover, the only overtones tried were harmonic to the fundamental. Some years ago I made an attempt to manufacture vowels on the principles discovered by the analysis of vowel curves.

The fundamental was produced by a puff siren (Fig. 7) similar to the familiar one of Seebeck. As a slit passes across the blast tube a jet of air issues for an instant. This is heard as a faint puff. As the disc is rotated more rapidly the puffs come oftener, until at one region a low tone appears. With still greater rapidity the pitch of the tone rises.

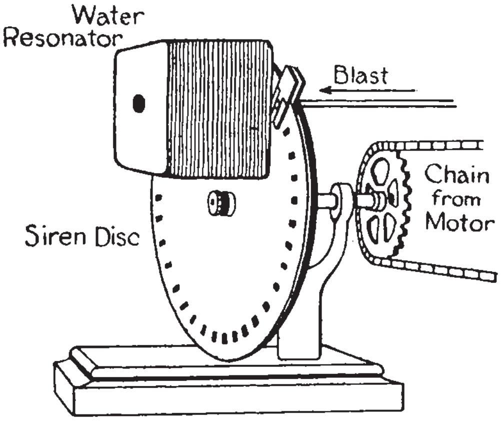

FIG. 7.—Puff siren with water resonator.

When a brass resonator is placed in front of the tube of the siren it sounds loudly when the frequency of the puffs is the same as that of the tone of the resonator, and also less loudly when it is in some other harmonic relation. For inharmonic relations the resonator is silent. Resonators with hard wells, therefore, cannot be used to produce sounds containing inharmonic components.

The soft-walled resonators of the mouth can be imitated by spreading pieces of meat over wire frames. As this has its inconveniences, a wire frame may be covered with a layer of absorbent cotton soaked in water. Such a resonator is shown in Fig. 7. The walls are quite inelastic. When such a water resonator is placed in front of the tube of the siren, it responds equally well to all tones of the siren, whether harmonic or inharmonic. Two or more resonators can be combined to meet the requirements for various vowels.

The theory of this vowel siren can be illustrated by the diagrams in Fig. 8. The puffs come as sharp blows almost instantaneous in character; they are indicated by the crosses. When such a blow strikes a resonator with soft walls, it arouses a vibration in the cavity that dies away very rapidly, as is indicated in the first line of the figure. The vibration is entirely gone before the next puff hits it. The response of the resonator is quite independent of the frequency of the puff. When, however, a puff strikes a resonator with hard walls, it arouses a vibration that dies away very slowly. When the next puff comes, the result depends on its relation to the vibration still going on in the cavity. If the puff hits the resonator at a moment when its frequency would be a sub-multiple of the frequency of the resonator, then it will reinforce the vibration and make the resonator tone louder. This is illustrated in the second line of the figure. If, on the other hand, it hits the resonator at a moment one-half a period short of a harmonic relation, it will kill the vibration it finds. A very weak tone may be aroused by puffs with a frequency that is not a sub-multiple of the frequency of the resonator, but no strong response can be obtained outside the harmonic relation.

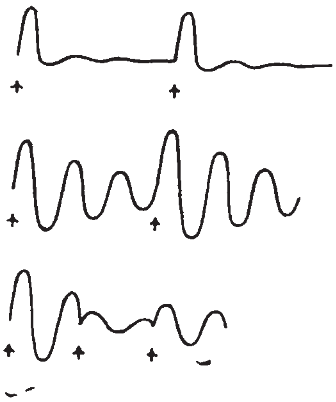

FIG. 8.—Vibrations in a resonator in response to puffs. The puffs are indicated by the crosses. The first line shows the response of a resonator with soft walls. In the second line the puffs hit a resonator with hard walls in such a way as to maintain strong vibrations. In the third line the puffs hit the same resonator in a way to produce little or no effect.

The siren with water resonators was constructed with the aid of the Hodgkins fund of the Smithsonian Institution of Washington. It produced most of the typical vowels with success. Under the Carnegie Institution the work was continued with an attempt to imitate more closely the conditions in the living body. Although the cheeks can be represented by water resonators, the roof of the tongue is somewhat more difficult; the roof of the mouth is quite an approach to a hard resonator. To imitate these conditions, a resonator was made of a skull supplied with cheeks and a tongue of gelatine. The tongue was removable, so that models of different forms could be inserted. The voice tone was obtained from a vox humana organ-pipe. The ultimate object was to find vowel resonators that would respond with specific vowels to any tone. These were then to be mounted on a reed organ as an extra register. All tones issuing from the organ could be made to pass through one of the vowel cavities, and the organ would thus sing the vowels. In most singing the consonants are a subordinate matter, and such an organ would aid the singing of a choir or a congregation. The beauty of such a vowel register in a large organ in a cathedral is quite beyond imagination. This investigation was also supported by the Hodgkins fund, but was discontinued on account of the work required for the study of speech curves.

The Structure of Vowels.

The study of speech curves and the making of vowel-producing instruments show that two groups of elements are to be found in a vowel.

The first is the voice tone. Three properties of this tone are to be considered. The pitch of the tone is given by the rapidity with which the laryngeal puffs are repeated. If V indicates the number of puffs per second, then $\mathrm{V}=f(t)$ is the general expression of the fact that the pitch of the voice tone depends on the elapsed time. It might be supposed that, in singing a vowel on a given note, the pitch would remain constant. A study of a record by the tenor Caruso (not yet published) shows that he never keeps his voice on a constant pitch during a vowel, but makes continual small changes. A study of the vowel "oh" used as an interjection shows that the pitch of the voice tone changes to express the emotion and the meaning of the interjection according as it is spoken to express sadness, admiration, or doubt. In fact, it is quite possible to obtain an equation for V for each of the three cases. In ordinary speech the pitch of the voice tone changes from instant to instant. Every individual vowel has a melody of its own. This melody varies with the emotion, the meaning, and possibly other factors.

The intensity of the voice tone depends on the energy of the puffs from the larynx. If I indicates the puff energy, then $\mathrm{I}=f(t)$ expresses the fact that the intensity varies from moment to moment. The speech curves show changes of intensity that express emotion and meaning. Even in song—as Caruso's curves show—the intensity is constantly varied in a way that makes his song a production of art, and not a mechanical performance.

The third factor of this group is the musical character of the voice tone. This depends on the *shape* of the puff from the larynx. The matter is of such importance that the following statement seems to be needed.

After a tuning-fork has been struck its vibrations slowly die away. Its curve is really not that of a simple sinusoid, but that of a frictional sinusoid

$$y=a\,.\,e^{-\epsilon t}\frac{2\pi}{\mathrm{T}}t, \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where y is the elongation at the moment t, a the amplitude or maximum elongation, T the period, e the basis of the natural system of logarithms, and ϵ the factor of friction or damping. The period T is affected by the factor of friction, but the amount is so small that it can be neglected here. The effect is to cause a decrease in the amplitude. When the value of ϵ is great, the curve is that of a sharp puff. When it is less, the puff is more gentle. If it were 0, the ordinary simple sinusoid would be obtained.

The puff from the larynx may be of a complicated form that should be represented by the sum of a series of frictional sinusoids. The complete equation would be

$$v=\Sigma a\,.\,e^{\;\epsilon t}\sin\frac{2\pi}{\mathrm{T}}t. \quad . \quad . \quad . \quad . \quad (2)$$

This comprises the whole of the vibration of a single puff. It is a free, and not a forced, vibration. The musical or unmusical quality of the voice depends solely on the presence or absence of the various members of (2). The quality of the voice that distinguishes a Caruso from a costermonger lies exclusively in the laryngeal puff. This fact is of importance as contradicting the almost universally accepted theory of vocal training that is based on "tone-placing" by the supposed action of the vocal cavities as resonators to give the musical quality to the tone from the larynx.

The other group of elements comprises the tones aroused in the vocal cavities. A puff striking a cavity arouses one or more vibrations of the form of a frictional sinusoid as in (1). Each cavity will have its own factor of friction and its own period. As shown by the vowel siren, this response will be a free vibration independent of the voice tone and the periods that go to the vibration that makes up the puff. Every change in the sizes or openings of the cavities will alter the periods of these vibrations. The possible combinations for the cavities of the chest, pharynx, mouth, and nose provide for an almost endless variety of vowels.

The speech curves show quite unexpectedly that there is no such thing as a constant vowel. The vowel "o" in "so" changes its specific vowel character from beginning to end. The least change is found in German; more change appears in American. There is so much change in English that an American hears the vowel "o." as a sound starting like "oh" and ending like "oo." The statement that this English vowel is a diphthong composed of two vowels is incorrect. The vowel is a single sound that gradually changes greatly in character. There is no objection to calling it a diphthong provided it be recognised—as the speech curves show—that all diphthongs are really single vowels that change greatly in character. At the same time, it must be recognised that what is called a single vowel may change even more in character than a so-called diphthong; the change in a very short vowel, as in "but," is often surprising.

Just what constitutes the differences between the different vowels is a problem at present beyond the reach of science. The ear tells us that there are many sounds which we group together under the type "ah"; many others that would go to form the type "oo," etc. The speech curves show that the multiplicity of varieties under each type is almost beyond belief. In a general way we know that the impression from "ah" is that of a higher tone than from "oo," from "ee" higher than from "ah," and so on. All details of the tones in a single vowel are lacking. Every investigator has differed from every other one in regard to what tones constitute any particular vowel. As shown in this article, we can get so far as to say on what principles a vowel is built up. We can even get curves of the vowels of an accuracy that leaves nothing to be desired. We have not, however, any method of analysing these curves accurately into a series of frictional sinusoids with independent periods and factors of friction. We must probably wait for some mathematician to do for this problem what Fourier did for harmonic motion.

Toxic Root-interference in Plants.

THE earlier investigations of the late Mr. Spencer Pickering at the Woburn Experimental Fruit Farm on the action of grass on fruit trees, which were described in the third (1903) and thirteenth (1911) reports issued from that station, sufficed to show that, in spite of some variability in degree, there is a definite deleterious effect on the health and development of fruit trees caused by grass grown immediately around them. That this is a general result and not a matter of special soil or other local conditions at Woburn has been demonstrated by independent experiments conducted in this country at Long Ashton, Wisley, and other places. So marked is the crippling effect of the grass in some cases that death of the trees has resulted. On the other hand, the presence of numerous grass orchards in apparently healthy and vigorous condition in many parts of the country made the existence of any direct toxic action on the part of the grass, such as Mr. Pickering was led to postulate, appear doubtful. It was evident that the action, if any, must be relatively complex, and the later work at Woburn now shows that this is so. In the seventeenth (1920) annual report from that centre new evidence is recorded which indicates not only direct toxicity of grass on fruit trees, but also a similar effect for any one plant on another when the two are grown in close association.

It is therein claimed that the action of grass is shown to be due to toxic substances derived from the grass, and is not the indirect result of any adverse effect on soil conditions as regards aeration, available moisture, or plant food. In a series of experiments in which apple trees were grown in pots and the grass in shallow, perforated trays resting on the soil of the pots, the injurious effect was secured, notwithstanding that the grass roots, by being confined to the soil in the tray, could neither impoverish the soil in the pot below, nor deprive it of oxygen or water. A similar result was obtained when the grass was grown in sand, instead of soil, in the perforated trays. The presence of grass roots in the soil in which the tree was growing was thus immaterial for the manifestation of the dwarfing effect, and it follows that nothing which might be abstracted from the soil by them could be held accountable for the results. The converse view that grass added to the soil something deleterious to the tree appears to offer the only explanation, the toxic material presumably being conveyed from the trays to the soil in the pots by means of the drainage water from the former. Direct evidence was secured on this point by utilising for watering the trees the leachings from the grass trays, the trays in this case not resting on the soil of the pots, but being placed elsewhere. The injurious effect on the tree was as marked as before. When, however, the leachings were allowed to stand for twenty-four hours exposed to the air before being used for watering the pots, the trees apparently were unaffected.

It was considered by Mr. Pickering that these experiments prove that the leachings contain an oxidisable substance derived from the roots of the grass which in its unoxidised form is detrimental to the growth of the trees, but after oxidation is no longer of a toxic character. The suggestion that it is nothing more than carbon dioxide given off by the grass roots was, according to him, disproved by the results of a series of experiments in which the plants were grown in pots as above, "with or without a surface crop in the trays, watering them in one case with ordinary water, in another case with a saturated solution of carbon dioxide, and in a third case with clear lime water, which, since lime absorbs carbon dioxide, would presumably have the reverse effect of the carbon